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The Near-Earth Space Radiation Environment for Electronics

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***Abstract*—The earth's space radiation environment is described in terms of: a) charged particles as relevant to effects on spacecraft electronics, b) the nature and distribution of trapped and transiting radiation, and c) their effect on electronic components.**

I. Introduction

The space radiation environment can have serious effects on spacecraft electronics. For example, accumulated damage from electron and proton exposure will limit system endurance. Transient effects from individual high-energy protons or cosmic rays can disrupt system operation, perhaps irreversibly. Of particular importance in assessing the impact of the space radiation on electronic devices are the limits in shielding effectiveness for high-energy electrons, protons, and cosmic rays.

Thus, the internal spacecraft radiation environment is defined by particle transport through the spacecraft structure and, when necessary, shielding added to protect sensitive electronic pieceparts.

Important effects on the internal electronics are performance degradation resulting from energy deposition by accumulated ionization in the semiconductor materials (total ionizing dose - TID); accumulated atomic displacement damage in the crystal semiconductors by high-energy protons (displacement damage); and transient effects resulting from the ionization tracks from the interaction of a single cosmic ray or high-energy proton (single event effects - SEE). Therefore, of particular interest for effects on the internal electronics are the total electron and proton exposure (i.e., fluence) and time-dependent rate of high-energy protons and cosmic rays (i.e., flux.).

II. Radiation Effects Trends in Modern Electronics

Trends over the last decade have been to increasingly use commercial (non-radiation hardened) electronics in spacecraft applications. This is due to a combination of economic and electrical performance reasons.

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However, this trend has not been without an emerging list of increased awareness of the effects and increased susceptibility of the space radiation environment on electronics. Among some of the emerging issues are:

- Scaled CMOS and reduced power supply voltages greatly increasing device susceptibility to SEUs,
- Increased complexity of devices leading to more complex error modes,
- Reduced electrical margins driving lower levels of radiation tolerance,
- New technologies such as dielectrics or materials (like SiGe) impacting the particle interaction modes, and,
- Effect of higher clock-speed operation on the propagation of single particle interactions increasing error rates.

This is not meant to be a comprehensive list, simply a few examples of the need to pay attention to how technology changes impact radiation performance.

III. The Trapped Radiation Environment

The Earth's natural radiation environment consists of electrons, protons, and heavy ions: a) trapped by the earth's magnetic field in the Van Allen belts, or b) transiting through the magnetosphere.

A characteristic of the geomagnetic field, of particular significance to space radiation effects in electronics, is the Brazilian or South Atlantic Anomaly (SAA). This is primarily the result of the offset of the dipole term of the geomagnetic field by approximately 11º from the earth's axis of rotation, and displacement of about 500 km toward the Western Pacific. The effect is an apparent depression of the magnetic field over the coast of Brazil. There, the Van Allen belts reach lower altitudes, extending down into the atmosphere. The SAA is responsible for most of the trapped radiation received in low earth orbits (LEO).

A. Trapped Radiation Domains

The Earth's magnetic field, above the dense atmosphere, is populated with trapped electrons, protons, and small amounts of low energy heavy ions. These particles gyrate around and bounce along magnetic field lines, and are reflected back and forth between pairs of conjugate mirror points (i.e., regions of maximum magnetic field strength along their trajectories) in opposite hemispheres. At the same time, because of their charge, electrons drift eastward around the earth, while protons and heavy ions drift westward. Fig. 1 [1] illustrates the spiral, bounce, and drift motion of the trapped particles.

The strong dependence of trapped particle fluxes on altitude and inclination is expressed through the McIlwain *L* parameter [2], where *L* is a dimensionless ratio of the Earth's radius, approximately equal to the geocentric distance of a field line in the geomagnetic equator.

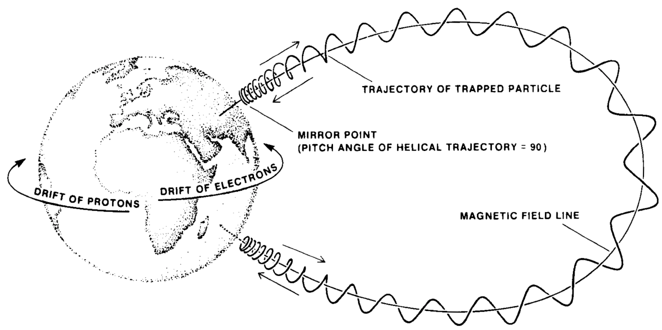

Fig. 1: Motions of trapped particles.

1) Electrons:

Energetic Van Allen belt electrons are distinguished into "inner zone" and "outer zone" populations. The volume of space occupied by the "inner zone" extends at the equator to about 2.0 R_e. The outer zone extends from about $L = 3$ to about $L = 12$. The region between $L = 2.0$ and 3.0 is called the "slot." During magnetospherically quiet times, its electron density is very low. However, during magnetic storms, the electron flux in the "slot" may increase by several orders of magnitude.

The inner zone electrons are less severe compared to the outer zone electrons. Specifically, the outer zone has peak fluxes exceeding those of the inner zone by about an order of magnitude. In addition, the outer zone spectra extend to much higher energies (~7 MeV) than the inner zone spectra (<5 MeV).

2) Protons:

In contrast to the electrons, the energetic trapped protons ($E > 1$ MeV) occupy a volume of space which varies inversely and monotonically with their energy as shown in Fig. 2. Consequently, these particles cannot be assigned to "inner" and "outer" zones. Fig. 3 shows the proton flux intensities as a function of radial distance and energy. In low earth orbits, the most intense and penetrating radiation is encountered in the form of protons in the SAA.

Periodically, major solar particle events (SPEs) have temporarily populated the "slot" region of the magnetosphere (L=2-3) with high intensities of energetic protons; that is, fluxes in the range of several thousands of particles per cm^2 per second, and energies greater than 10 MeV. These have shown decay times of 6-9 months.

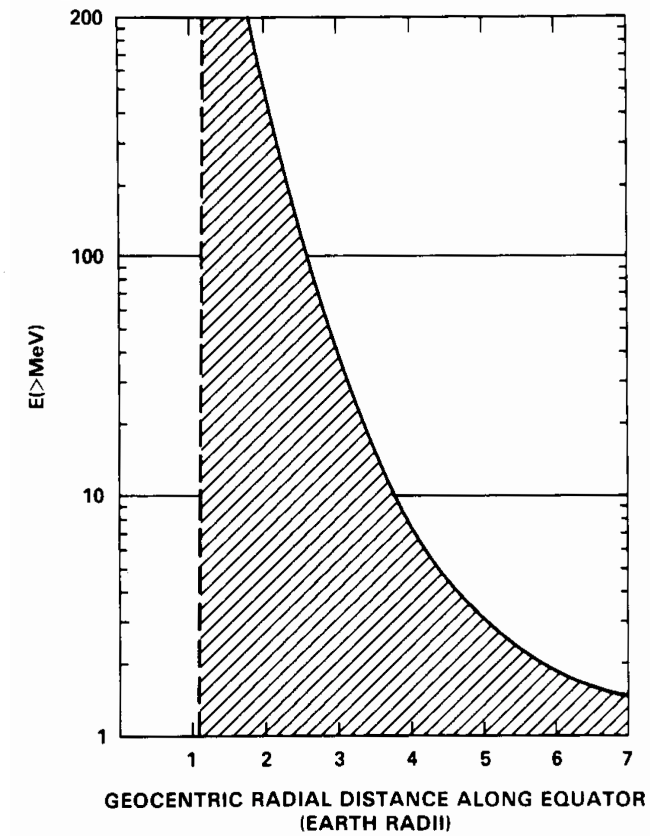

Fig. 2: Trapped proton population as function of energy.

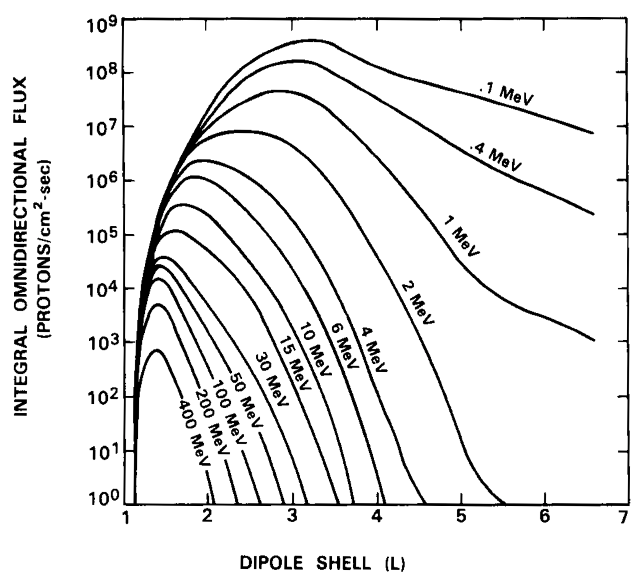

Fig. 3: Equatorial radial profiles for proton fluxes.

B. Models

Available radiation measurements from space form the basis for models of the trapped electron and proton environment. These models have been developed by the U.S. National Space Science Data Center (NSSDC) at NASA's Goddard Space Flight Center. All models are constructed with several dozen data sets from a corresponding number of satellites, providing a wide spatial and a long temporal coverage.

The most recent of these models, AP8 for protons [3] and AE8 for electrons [4] are available in solar minimum and solar maximum versions. They permit long term average predictions of trapped particle fluxes encountered in any orbit.

C. Variations

The trapped particle fluxes respond to changes in the geomagnetic field induced by solar activity, and, therefore, exhibit a strong dynamic behavior, especially in the outer belt.

As mentioned previously, the South Atlantic Anomaly is a region of trapped particle radiation close to the Earth. Hence, for low altitude, low inclination orbits, the SAA is the most important factor in determining the level of radiation exposure of spacecraft. For low earth orbits with higher inclinations (>35º), the protrusions of the outer zone electron belts (the electron "horns") in the mid-latitude regions must also be considered. Of particular importance is the temporal distribution of the proton exposure, which determines the maximum rate of potential proton-induced single event upsets (SEU) in the electronics, as well as the periods in which no upsets will be observed.

D. Artificial Enhancement

A severe hazard for space missions could be introduced by a high altitude nuclear explosion. Such an effect would result in the injection into the magnetosphere of energetic electrons from the beta decay of fission fragments. Subsequent trapping of the electrons in the magnetic field [5] could produce an enhancement of the electron population by many orders of magnitude.

The principal hazard would be to missions in low earth orbits, mainly because of an expected very stable trapping with lifetimes up to eight years [5]. Fig. 4 shows the isochronal contours for the trapped electrons resulting from the STARFISH exoatmospheric nuclear explosion of July 1962 over Johnston Island in the Pacific. However, depending on the location of the explosion, the injection could also produce a temporary large enhancement of the electron environment at geostationary orbits. At GEO, the trapping would be less stable, with exponential decay periods of between 10 and 20 days. The apparent longevity, or conversely, the decay rate, of such fission electrons depends to a large extent on the injection latitude and altitude; that is, it is a function of the magnetic dipole shell parameter L and, to a lesser degree, of magnetic field strength [6].

For the internal electronics, it is important to note that both the total ionizing exposure level and exposure dose rate are substantially increased by the artificially enhanced environment.

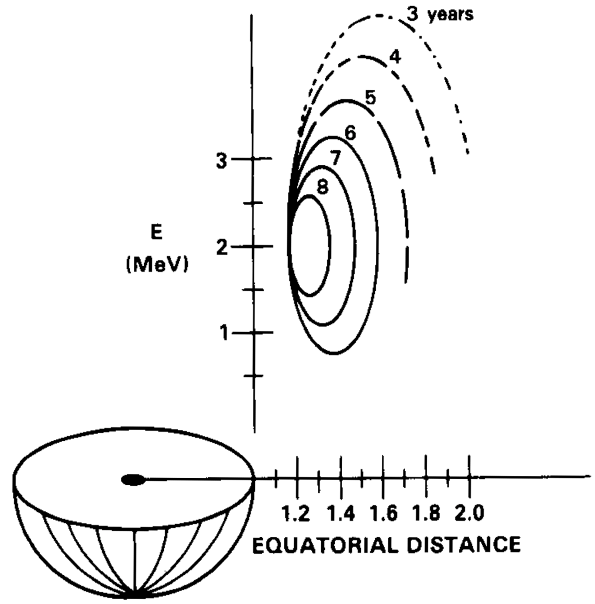

Fig. 4: Isochronal contours for STARFISH electron longevity.

IV. TRAPPED RADIATION TRANSPORT, SHIELDING, AND DOSES

A. Emerging Primary and Secondary Radiation

In interacting with spacecraft materials, the electrons and protons of the trapped radiation belts are modified in intensity by shielding, and modified in character through the production of secondary radiation. The secondary radiation can extend the penetration of the primary radiation and lead to an increase in dose deposition. The most significant secondary radiation is the bremsstrahlung, or "braking radiation," produced in the deceleration of electrons penetrating the spacecraft. This is a continuous X-ray spectrum emitted roughly in the direction of electron penetration. Bremsstrahlung from energetic electrons populating the radiation belts is very penetrating, and thus difficult to attenuate, especially with the low-atomic number materials popular on spacecraft (e.g., aluminum). On the other hand, these low-atomic number materials tend to produce less bremsstrahlung.

B. Variables Affecting Dose Evaluations

Obtaining estimates of the dose on a given component of the internal electronics in a spacecraft is a complex process involving several variables that directly affect the results. These variables include: 1) primary environment definition, 2) description of the input spectra, and 3) contributions from secondary particles and protons.

Additionally, four areas stand out that are of particular concern to shielding and transport evaluations. These are completely independent from, and unrelated to, the definition of the spacecraft-encountered radiation environment. These areas are: 1) shield geometry and shielding analysis technique, 2) shield material composition, 3) target (i.e., component) composition (e.g., package, passivation, metallization and semiconductor of a complex microcircuit), and 4) dose units. Each of these offers a multiplicity of choices and conditions that need to be clearly identified and defined whenever calculations are performed and results presented. Otherwise, the comparison of dose data compiled by several independent sources, although derived from the same spacecraft surface incident spectrum, becomes meaningless and futile. In such cases, disagreements by factors up to 20 have been known to occur.

Energy deposition in the internal electronics is measured in units of rads (material). A rad (radiation absorbed dose) is defined as 100 ergs of energy deposition per gram of absorber material, without reference to the nature of the energy deposition. The MKS equivalent of the rad is the Gray, which is defined as the energy deposition of 1 Joule in one kg of material (e.g., 100 rad(Al) = 1 Gy(Al)). For electron exposure, the energy deposition is almost all by ionization. For proton exposure, the energy deposition includes both ionization and atomic displacements.

C. Permanent Damage Susceptibility of Electronics

The basic permanent damage mechanisms in semiconductor devices exposed to high-energy electrons and protons are accumulated ionization effects and atomic displacements in bulk semiconductors. Energy deposition from electrons and protons includes both ionization and nonionization. Effects of electron exposure in virtually all modern microcircuits are dominated by accumulated ionization. Definition of the internal ionizing radiation environment in terms of rads(Si) is generally adequate. Failure levels resulting from accumulated ionization can be as low as approximately 1000 rads(Si) for very sensitive unhardened microcircuits to greater than 10 Megarads(Si) for hardened microcircuits [7].

Effects of proton exposure over the energy range of interest in the space environment include both ionization and atomic displacement damage [8]. Failure levels resulting from proton-induced displacement damage can be as low as $1x10^{10}$ p/cm^2 for very sensitive bipolar analog microcircuits or power transistors. In general, however, effects of proton exposure on the internal electronics are dominated by the ionizing energy deposition [7]. Definition of the proton environment for the internal electronics should include both the proton-induced energy deposition (in rads(Si)), and the internal proton fluence and energy spectra for accurate characterization.

D. Single Event Susceptibility of Electronics

The high energy protons of the trapped space radiation environment can cause single event effects in modern semiconductor electronics. The proton energy threshold for these effects is approximately 10 MeV with the cross section for nuclear reactions increasing substantially at 30 MeV and above [8]. Typically, a nuclear reaction resulting in a single event occurs on the order of once for every 100,000 protons. In terms of microcircuits susceptibility, for a 60º orbit, the maximum proton-induced upset rate occurs in the heart of the proton trapping domain of the radiation belts at an altitude of approximately 2600 km. It has been estimated that for electronics with “typical” shielding, the single event upset rate could be as high as 0.1 upsets/bit-day for very susceptible microcircuit technologies, decreasing by at least five orders of magnitude for less susceptible microcircuit technologies [9].

At low altitudes, low inclination orbits, the proton induced single event upset rate is determined by passages through the South Atlantic Anomaly.

It should be noted that SEEs can be “soft” or “hard”; i.e. a bit flip or a destructive event.

V. TRANSITING RADIATION

The transiting radiation of the space radiation environment is composed of a solar contribution and a galactic contribution. Each is composed of high energy protons and heavy ions. In terms of the spacecraft electronics, the dominant effects are those associated with the ionization tracks of single particles, as well as the effects of total accumulated ionization.

A. Solar Cosmic Rays

1) Solar Proton Events

Distributed regions on the sun sporadically emit bursts of energetic charged particles into interplanetary space. These solar energetic particles (SEP) events, usually occurring in association with solar flares or coronal mass ejections (CMEs), are composed primarily of protons, with a minor constituent of alpha particles (5-10 percent), heavy ions, and electrons. The emission of protons from the SEP event can last as long as several days.

SEP event phenomenology distinguishes between several magnitudes of events. Extremely large events are quite rare. Three such events occurred during the 19th solar cycle, one during the 20th cycle, none in the 21st cycle [10], and five during the 22nd cycle [11]. They occur mostly near the first and last year of the solar maximum phase. The prediction of such events was initially based on an empirical model [12], and later on a probabilistic treatment involving modified Poisson statistics [13].

2) Solar Heavy Ions

For most solar events, the relative abundance of the helium ions in the emitted particle fluxes is usually between 5 and 10 percent, while the fluxes of heavier ions are very small, and significantly below the galactic background. However, during major solar events, the abundance of some heavy ions may increase rapidly by three or four orders of magnitude above the galactic background, for periods of several hours to days. The increased flux of the heavy ions can have serious consequences in terms of an increased frequency of single event effects within the spacecraft electronics.

B. Galactic Cosmic Rays

The region outside the solar system in the outer part of the galaxy is believed to be filled uniformly with cosmic rays. These consist of about 85 percent protons, about 14 percent alpha particles, and about 1 percent heavier nuclei. The galactic cosmic rays range in energy to above 10 GeV per nucleon. The differential energy spectra of the cosmic rays near the earth tend to peak around 1 GeV/nucleon. Toward lower energies, the spectral shape is depressed by interactions with the solar wind and the interplanetary magnetic field. This reduction in flux becomes pronounced during the active phase of the solar cycle. The total flux of cosmic ray particles seen outside the magnetosphere at the distance of the earth from the sun (i.e., 1AU) is approximately 4 per square-centimeter per second (primarily composed of protons). For all practical purposes, the cosmic ray flux can be considered as omnidirectional, except for very low altitude orbits, where the solid angle subtended by the earth defines a region free from these particles. A model of these particles is available [14].

C. Geomagnetic Shielding

Low altitude and latitude earth orbits are essentially shielded from solar or galactic cosmic rays by the geomagnetic field up to inclinations of about 45°. The earth's field acts as an energy filter preventing particles with less than given momentum values from penetrating to certain altitude-latitude combinations. Fig. 5 shows the total ion energy required to penetrate the magnetosphere in terms of the dipole shell parameter *L*.

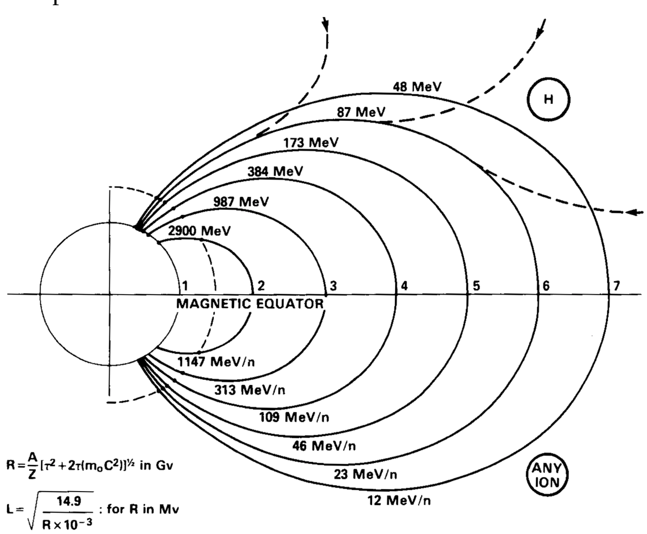

Fig. 5: Total energy required to penetrate the magnetosphere.

V. Cosmic Ray Transport, Shielding, and Energy Deposition

A. Emerging Radiation Spectra

1) Solar Proton Events

Considerations in the transport of solar protons are similar to those previously discussed for the trapped protons. The materially attenuated emerging spectra reflect the shielding effects on the distribution of the solar protons. The proton fluxes in the 0.1 to 10 MeV range emerging behind spherical aluminum shields of thickness ranges from 0.3 to 5 grams/cm^2 are substantial. Particularly relevant to single particle event effects in the electronics is the Linear Energy Transfer (LET) in silicon, defined s the energy deposition per unit length in the active region of the semiconductor device.

In general, the ionization loss of a single proton is insufficient to cause a single event effect in a semiconductor device. However, certain technologies, such as fiber optic links, may be susceptible to this direct ionization mechanism. Observed single event effects from proton exposures are more typically the result of the energy deposition of particles produced by nuclear interactions by the incident proton with the target nucleus. The proton threshold energy for these nuclear interactions is approximately 30 MeV [9].

2) Galactic Cosmic Rays

The LET spectrum is important in defining the energy deposited by a single particle, and subsequent single event effects in the spacecraft electronics.

In passing through shielding material, nuclear reactions are induced by heavy ions with energies above an effective threshold of a few MeV/nucleon. These nuclear reactions provide a source of secondary radiation, both prompt and delayed. Above several hundred MeV/nucleon, nuclear reactions surpass atomic ionization as the main attenuation mechanism in material. At higher energies, the interaction of the incident particle tends to occur primarily with individual nucleons in the target nucleus, and can lead to the ejection of several energetic protons and neutrons. This "spallation" process leaves the product nucleus highly enxited, with de-excitation occurring through the "evaporation" of additional nucleons and the emission of gamma rays. For 400 MeV protons incident on aluminum, the average total nuclear emission is 4.8, including 2.8 spallation nucleons with an average energy of 120 MeV [15]. The process can generate a rich variety of residual nuclei, especially in heavier elements, as a result of the multiplicity of statistically possible reaction paths (i.e., the specific number of protons and neutrons emitted). These product nuclei frequently are radioisotopes decaying by beta-ray emission with a variety of lifetimes.

With increasing shield thicknesses, the population of high energy ions decreases slightly, but with a resultant increase in the low energy (0.8-50 MeV/nuclear) ions. Since the LET increases with decreasing energy in this range the presence of the shield actually increases the severity of the environment to the internal electronics.

B. Ionizing Radiation Dose

In general, the ionizing radiation dose from the transiting radiation environment is not significant compared to that of the trapped radiation environment. Particle fluxes from energetic solar particle events are heavily attenuated by the geomagnetic field, which prevents their penetration to low orbital altitudes and inclinations.

Orbits such as polar may have issues with technologies such as solar arrays and imagers.

C. Single Event Susceptibility of Electronics

Single event upset effects in electronics from the transiting space radiation environment may be the result of either the energetic solar protons or galactic cosmic rays. In general, the single event upset rate due to transiting protons (whether solar or galactic) is small compared to that due to the heavier cosmic rays, except for the occurrence of an extremely large solar particle event. To cover the occurrence of such an event during the spacecraft mission, both the expected duration and fluence of the event must be considered in the electronics design.

For the heavier than hydrogen cosmic ray component of the transiting space radiation environment, the definition of the LET spectrum of the internal radiation environment is a fundamental basis for characterization of component susceptibility. Observed events from single heavy high-energy ions include memory bit upset, microprocessor errors, CMOS latchup and burnout in power MOSFETs, and electrically-erasable PROMs [16], [17]. The probability of latchup or burnout is much less than that of memory bit upset or logic errors, but the consequences to system operation may be much more severe.

Generally, cosmic-ray-induced single event effects dominate proton-induced single event effects both at altitudes below 1000 km and above 4000 km for 60º circular orbits. For orbits of lower inclinations, the cosmic rays are shielded by the earth's magnetic field, causing the cosmic ray upset level to decrease compared to the trapped proton upset rate. On the other hand, for orbits of higher inclinations, the relative upset rate of the cosmic rays increases. The specification of the internal electronics environment should include the time-dependent proton flux and energy spectrum, the cosmic ray LET spectrum, and the cosmic ray spectrum by particle species and energy spectrum. The actual cosmic ray spectrum can be a valuable supplement to the LET spectrum in those cases where more detail is necessary to support experimental characterization in ground-based laboratory facilities.

VI. Conclusion

The richly diverse terrestrial space radiation environment has been described in terms of its nature and variations with respect to the susceptibility of spacecraft electronics. The constraints of space radiation effects on spacecraft electronics design can be significant, but with careful component selection, shielding, and design, systems can be realized that are both of high performance and long endurance. However, new technology issues need to be understood to increase system reliability.

This paper has specifically addressed the earth radiation environment, but our planet is not alone in its magnetic field and trapped radiation belts. Jupiter has a trapped radiation environment much more severe than that of the earth. Even in transit to the outer planets and beyond, the galactic cosmic rays must be considered in their effects on the electronics. As our knowledge of the space radiation environments and radiation effects of electronics grows, the electronics technology itself evolves. The combination will be both exciting and challenging for many years to come.

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